PARTICULATE SOURCE STRENGTH DETERMINATION FOR LOW-INTENSITY PRESCRIBED FIRES

Darold E. Ward, Ernest R. Elliott,
Charles K. McMahon, Dale D. Wade
Southeastern Forest Experiment Station
Southern Forest Fire Laboratory
Forest Service, U. S. Department of Agriculture
Macon, Georgia

Prescribed fire is the intentional use of fire to achieve certain land management goals. Over 2 million acres of forest land in the southern United States are treated with this tool each year. The benefits from these burns can be offset by a degradation of air quality due to the improper management of combustion products. This paper reports on a portion of the overall research program at the Southern Forest Fire Laboratory which is designed to provide smoke management guidelines to land management personnel.

Included is a description of a method for determining particulate source strength emission factors for low-intensity prescribed fires. A limited amount of data regarding source strength, smoke concentration, and particulate size distribution for 9 natural environment prescribed fires is presented. Results are compared with previous data collected from fuel samples burned in the combustion room at the laboratory.

Comparability was found between the concentrations of particulates determined while sampling side-by-side with the high-volume air sampler, the Andersen sampler, and open-faced 47 mm filters.

Significant differences in particle size distributions were found between fuel types. Artificially produced fuel beds in the laboratory yielded lower particulate production rates than fires in undisturbed natural fuels in the forest. Particulate concentrations were found to be excessive near the fire, 60,000 $\mu g/m^3$, but decreased to less than 30,000 $\mu g/m3$ 10 feet away.

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Introduction

Prescribed fire, a type of planned open burning, is used extensively in the southeastern United States for applying specific resource management treatments to our forests. In excess of two million acres of forest land are treated annually in the 13 Southern States using low-intensity prescription fires. Prescribed fire has proved to be more economical than alternative mechanical treatments and, in some cases, is the only known practical method for achieving hazard reduction, undesirable species control, wildlife habitat improvement, and other management requirments. Along with the benefits derived from the prescribed use of fire are combustion products, some of which degrade air quality if not properly managed. The impact of this intentional burning on air quality is being studied at the Southern Forest Fire Laboratory. Our mission is to develop smoke management guidelines which will assist foresters with their job of prescribing land management treatments. Basic to these guidelines is knowledge regarding the rate of emission of smoke particulates from the burning of various fuels under various weather conditions.

The research problem is being studied both from controlled environment laboratory studies and through natural environment field research. This paper will concern itself mainly with the field approach. However, for comparative purposes the controlled environment combustion room study results will be presented. These emission factors were derived by using the following techniques:

1. Uniformly distributing a known oven dry weight of fuel on a 3x4-ft wire basket fuel bed.

2. Conditioning the fuel to the desired equilibrium moisture content by regulating the atmospheric moisture and temperature.

3. Placing the fuel bed on a slope table located in the geometric center of the floor under the hood and stack in an environmentally conditioned 30-ft cubical combustion room.

4. Igniting a line of fire along the 3-ft side of the fuel bed, either at the top to simulate a fire backing into the wind (Figure 1), or at the bottom simulating a fire heading with the wind, burning upslope.

5. Isokinetic sampling of the emissions passing through the 24-in. diameter stack trapping the particulates in a standard 8x10-in. Type A glass fiber filter mat.

Using these techniques, particulate emission factors for the fuels burned ranged from 6 to 158 pounds per ton of fuel consumed (Table I). In general, particulate production increased with increased fuel moisture content and decreased as the rate of spread decreased. In the natural environment this is comparable to using a fire backing into the wind versus a head fire running with the wind. These controlled environment studies are continuing, with emphasis being placed on particle size distribution changes with fuel alterations and in determining additional emission factors for other fuel types.

Field Experimental Methods

Laboratory-derived emission factors are being checked under natural environmental conditions. We have concentrated on two major fuel types commonly burned in the Southeast. These fuels, gallberry-palmetto and slash pine (*Pinus elliottii*) needle litter fuels, are primarily burned using low-intensity backfires (Figures 2 and 3). The emissions from backfires generally rise on a gentle, inclined plane as the wind disperses the smoke away from the fire.

A method for monitoring smoke concentration at various horizontal and vertical spatial points downwind from low-intensity line source backfires was first developed. By positioning samplers in the vertical dimension with the top samplers above the smoke plume and by knowing the amount of air moving past this vertical array of samplers, an emission rate can be calculated for the fire.

Five 40-ft masts were constructed out of 10-ft sections of rigid aluminum conduit tapering from 2 in. in diameter at the base to 1 in. at the top. The mast is in two sections to facilitate transporting. Samplers, each containing a 47 mm Type A glass fiber filter, are positioned at various heights on the mast. A central vacuum source with a capacity of 10 cubic feet of air at 20 in. of Hg is used to service the five masts. Each mast acts as a vacuum manifold, and each filter is attached to a critical flow-limiting orifice. These are 18 gauge, 1-1/2-in. long, hypodermic needles which maintain a constant, critical flow of approximately 4 liter per minute (Lodge, et al., 1966)[1]. The hypodermic needle is inserted through a pilot hole in a 00 rubber stopper which in turn is inserted into drilled holes along the mast at the desired heights. The constant flow rate orifices are calibrated periodically, using a wet test gas meter.

A typical field test involves first sampling the fuel to determine the weight of fuel on the site. Usually equipment for monitoring wind direction and speed is operated adjacent to the planned burn area. Orientation of the fire line must be established perpendicular to the wind direction. Five masts are then outfitted with pre-weighed filters (environmentally conditioned at 50% relative humidity and 70°F) in each sampler. The towers are raised (a task easily handled by two men) and secured to 2-in. x 4-ft angle irons driven into the ground. Vacuum lines are attached to each mast and a check is made for leaks. Standard high-volume air samplers are located within 5 feet of each of the three masts nearest the fire. The larger mass of particulate matter collected by these samplers will be used for chemical extraction purposes. An 8-stage Andersen nonviable particle sampler is located near the center high-volume sampler and mast. These samplers, as explained here and in the next section, each have a specific function as well as providing a means for cross-checking results. Figure 4 is a plan view of the equipment relative to the area to be burned.

Results

Particulate Concentration

Prescribed fires usually only last a few hours, the exception being fire used for reducing piled slash. In most cases, prescribed fires are used rotationally covering a given area once every 3 to 5 years. These fires are generally set from, or burn to, roadways. Usually this creates no serious visibility problem, but under certain conditions can impede travel. In developing smoke management guidelines, we are attempting to quantify situations along roadways when prescribed fires can be used with little risk of reducing visibility.

The grid of masts shown in Figure 4 measure particulate concentration immediately downwind from the fires. An example of the average smoke concentration over a 20-min sample time is illustrated by the isopleth diagram in Figure 5. Thirty feet downwind, the particulate concentration 3 ft above the ground decreased from 26,000 $\mu g/m^3$ to about 10,000 $\mu g/m^3$ with a further decrease to about 3000 $\mu g/m^3$ 60 feet from the fire line.

Other fires have been sampled by taking 5-min incremental samples as the fires backed into the wind away from the masts. For one fire, samples taken at 3 and 6 ft above the ground show a maximum concentration within 5 ft of the fire of 60,000 $\mu g/m^3$. During the first 15 minutes this concentration decreased by one-half as the fire moved 10 ft away from the mast.

Particulate concentration is a function of wind speed, vertical temperature profile, fire heat yield rate, as well as the rate of emission of particulates. As more fire situations are sampled, correlations will be drawn between smoke concentration and different fire and weather variables.

Source Strength Determination

Particulate source strength data for forest fuels have been determined by burning fuel samples under hoods (Gerstle and Kemnitz, 1967)[2], Darley, et al. 1966)[3] and in combustion chambers (see introduction). These fuel samples in general have been artificially arranged and have not utilized naturally layered, conditioned and compacted fuels. An exception is Boubel, et al. (1969)[4] work with actual stubble and straw. There is a need to correlate source strength data from the artificially controlled environment with those measurements of source strength made under natural environmental conditions. We still know very little about particulate production rates for fuels burned at times when only the surface layer of needles is consumed overlaying a very wet lower layer. As the forest floor dries, consumption of the fuel complex becomes greater. This results in deeper layers of partially decayed fuel being consumed, which may contribute considerable particulate matter in addition to that produced from the surface layer of fresh pine needles.

Source strength data have been obtained for a number of individual fires by using the masts to determine smoke concentration with height. Totalizing anemometers located at 6 and 20 feet above the ground are used to determine the number of feet of windrun past the mast during each sample period. An example of the calculations is given for a fire in a palmetto-gallberry fuel complex (see Table II). These calculations indicate that the fire produced 4.89 g of particulates per minute per foot of fire line. In this case, the fire line was about 1320 feet in length. The fire was yielding approximately 6.5 kg/min. The emission factor for the palmetto-gallberry fuel was calculated to be 27.3 lb/ton of fuel consumed. Other fuel situations have been sampled and are summarized in Table III.

Fires in the palmetto-gallberry fuel type consumed more fuel per acre and had higher spread rates than those in the slash pine litter fuels (Table III). The slash pine litter fuels were burned under two rather divergent moisture regimes with consumption and rate of fire spread significantly less under the wetter condition. Particulate production rates were much lower for the wetter fuels, but emission factors were similar under both moisture regimes. However, the difference in particulate emissions between fuel types appears to be highly significant. On the other hand, particulate emissions determined for loblolly pine litter fuels in the laboratory (Table I) showed a dependency on fuel moisture content.

Particulate Size Distribution

A partial description of size distribution of particulates from low-intensity prescribed fires has been obtained using the Andersen non-viable 8-stage particle sampler. Particles are sized aerodynamically (Anderson, 1966)[5]. The larger sized particles are impacted on the first stages with progressively smaller sized particles being collected on the later stages. A backup filter is used to collect those particles smaller than about 0.40 μ (47 mm, Type A, glass fiber).

Each stage was covered with an aluminum disc (3.25 in. in diam) cut from household foil, which made a low tare weight collection surface. All foil discs were conditioned at 50% relative humidity and 68°F for 24 hr prior to weighing.

MacArthur (1966)[6] reported a preponderance of particles by number of 0.1 μ diam from forest fire smoke. His analysis through electron and light microscopy indicated few particles in the 0.5 to 1 μ range or larger. His samples were collected at altitudes from 1000 to 1500 feet over terrain. Our sampling with the Andersen sampler, done in close proximity to the fire, tends to support MacArthur's findings. We found a majority of the mass of particulates to be less than 0.4 μ in size (Table IV). Our sampling showed little variation for the slash pine litter fuel type burned under two divergent moisture content conditions. However, we did find that the particle size distribution shifts with a change in fuel type. In the palmetto-gallberry fuel type about 50% of the particulates by weight were aerodynamically sized less than 0.4 μ, while in the slash pine litter fuel type 70% were collected in the final filter.

Particulate Concentration Comparability

On several of the test fires particulate concentration was sampled using three different techniques. These methods (47 mm filter sampler, high-volume air sampler in a standard shelter, and the Andersen sampler) have produced comparable data. An example collected February 21, 1974, which is the average for three replicated test fires, is as follows:

Method	Particulate Concentration ($\mu g/m^3$)
47 mm filter	8280
Andersen	7120
High-volume	8502

Conclusions

Some of the tentative conclusions are:

1. Particulate concentration decreases rapidly with distance from the edge of the prescribed fires sampled. Wind speeds of about 2 mph have diffused smoke concentration by a factor of 2 within 50 ft of the fire.

2. Particulate production appears to be higher from undisturbed fuel complexes burned in the natural environment than the emissions from artificially prepared fuel beds burned in our combustion room.

3. Aerodynamic sizing of aerosols produced from natural fuels has demonstrated a marked difference between fuel types.

4. Comparability in measuring smoke aerosol concentrations has been achieved between the Andersen inertial sampler, the hi-volume air sampler, and open-faced 47 mm filters.

More importantly, the data generated and technique illustrated can be used for determining source strength for low-intensity prescribed fires. This is providing information to meteorologists who are using models for predicting particulate concentration in the smoke plume farther downwind.

Knowing the source strength, smoke concentration, and particulate size distribution for low-intensity prescribed fires burned under different fuel and weather conditions is a major step in the development of smoke management guidelines.

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KEY WORDS

EMISSION FACTORS, SOURCE STRENGTH, OPEN BURNING, PRESCRIBED FIRE, PARTICULATE SMOKE CONCENTRATION.

Table I Particulate emission factors (lb/ton) for various fuel and burning techniques.

Fuel	Per cent moisture content	Slope (per cent): Backfire (simulated) -50	-25	0	Head fire (simulated) +25	+50	+75
Loblolly pine (loose)	6	15	19	28	47	40	
Loblolly pine (loose)	10	13	20	37	67	55	
Loblolly pine (compacted)	18	28		86	123	158	152
Loblolly pine (branches & twigs 1/4 - 1 in.)	15			6			
Goldenrod	10			6			
Mixed grasses (compacted)	12			34			
Hardwood leaves (red oak)	11			7			

Table II An example of the method used for computing the particulate emission rate. Data are from the palmetto-gallberry type. Sample time was 20 minutes.

Sampler height (ft)	Mast No.[1/] 1	Mast No. 2	Mast No. 3	Partic.[2/] conc. mean	Window[3/] area (ft^2)	Wind run (ft)	Vol.[4/] of air (m^3)	Mass of[5/] particulate (g/ft of fire line)
	- - - - -	(mg/m^3)	- - - - -					
3	34.6	21.4	23.7	26.57	4.5	6500	828	22.01
6	30.5	23.6	21.8	25.30	3	6550	556	14.08
9	24.8	20.6	20.0	21.80	4	6450	731	15.93
14	15.3	16.1	17.3	16.23	5	6250	885	14.36
19	9.9	10.9	13.5	11.43	5	6030	854	9.76
24	7.0	7.3	10.3	8.20	5	6000	850	6.97
29	6.2	5.6	8.2	6.67	5	6000	850	5.67
34	3.7	5.8	7.3	5.60	5	6000	850	4.76
39	3.6	4.0	7.7	5.10	5	6000	850	4.33
								97.87g

1/ See Figure 4 for location of masts 1, 2, and 3.

2/ Average of the 3 masts (Figure 5).

3/ A window 1-ft wide parallel to the fire line is used.

4/ Volume of air passing through each window.

5/ Mass = (mean conc)(area)(wind)($.02832m^3/ft^3$)
Production rate/ft of fire line = total mass/sample time
= 98.87g/20 min
= 4.89g/min/ft of fire line

Table III Particulate emission rates and factors for two different fuel types burned using low-intensity backfires.

Fuel type	Moisture content1/ (%) Upper	Moisture content1/ (%) Composite	Fuel consumption (tons/acre)	Sample time (min)	Fire spread (ft/min)	Length of fire line (ft)	Particulate production rate: Per ft of fire line (g/min)	Particulate production rate: Entire fire (kg/min)	Emission factor (lb/ton)
Litter (slash pine)	23	84	3.4	45	0.39	250	0.66	0.165	47.7
	23	84	3.7	45	0.40	250	0.66	0.165	43.0
	23	84	3.0	45	0.41	250	0.59	0.148	46.1
Litter (slash pine)	None	None	5.8	40	0.60	250	1.88	0.470	51.3
	25	54	5.4	30	0.63	530	1.74	0.922	49.2
	13	36	5.2	30	0.61	530	1.70	0.902	51.5
Palmetto-gallberry	17	82	5.0	45	1.38	660	1.92	1.268	26.8
	22	69	6.4	25	2.91	660	3.01	1.985	15.5
	10	72	9.9	20	1.74	1320	4.89	6.452	27.3

1/ Upper moisture content is the moisture content as a per cent of oven dry weight of this year's needle fall.
Composite moisture content is the average moisture content of those fuels consumed.

Table IV Size distribution difference between slash pine litter fuel burned at two moisture content levels and palmetto-gallberry fuel. Data collected using Andersen sampler.

Andersen stage	ECD 1/ (microns)	Per cent of total weight by fuel type		
		Slash pine 2/	Slash pine 3/	Palmetto-gallberry 4/
0	11 & above	1.0	0.9	1.1
1	7	0.7	0.3	1.0
2	4.7	0.9	0.7	0.9
3	3.3	0.7	0.9	1.3
4	2.1	1.7	1.8	4.3
5	1.1	4.3	4.6	6.5
6	0.65	5.0	9.0	12.3
7	0.43	12.6	11.7	19.4
Backup filter	----	73.1	70.0	53.1
Particulate concentration		5,199 $\mu g/m^3$	17,834 $\mu g/m^3$	11,543 $\mu g/m^3$

1/ Equivalent cutoff diameter which assumes spherical particles of unit density.
2/ Average of four samples. Upper moisture content = 23%, composite moisture content = 84%.
3/ Single observation. Upper moisture content = 19%, composite moisture content = 45%.
4/ Average of three samples. Upper moisture content = 18%, composite moisture content = 71%.

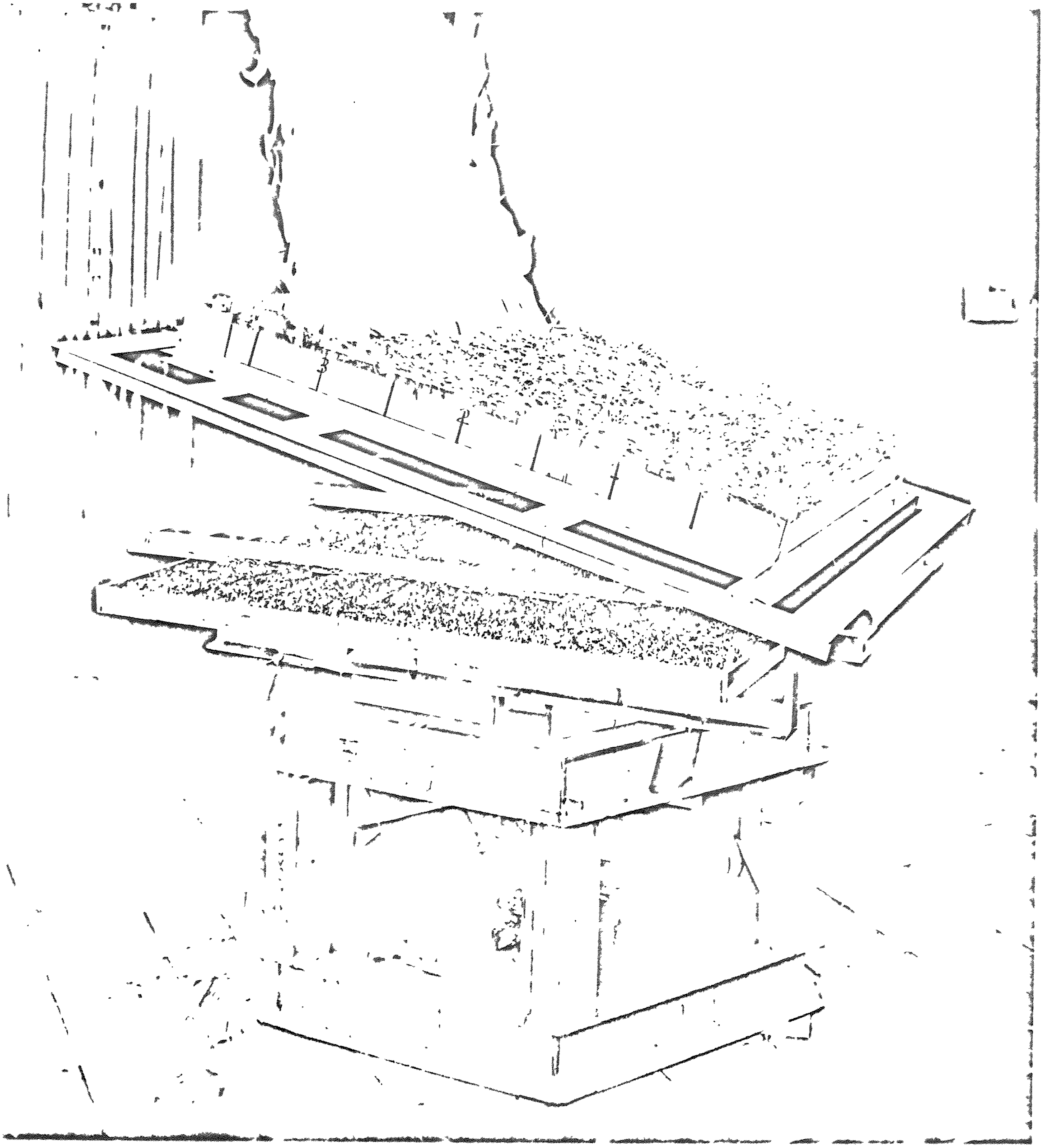


Figure 1 Test of a simulated backfire consuming loblolly pine needle litter fuel in a 3x4-¼in wire basket on a weight-loss sensing slope table.

Figure 2 A typical prescribed fire backing into the wind through a palmetto-gallberry fuel complex.

Figure 3 A typical prescribed fire backing into the wind through a slash pine needle fuel complex.

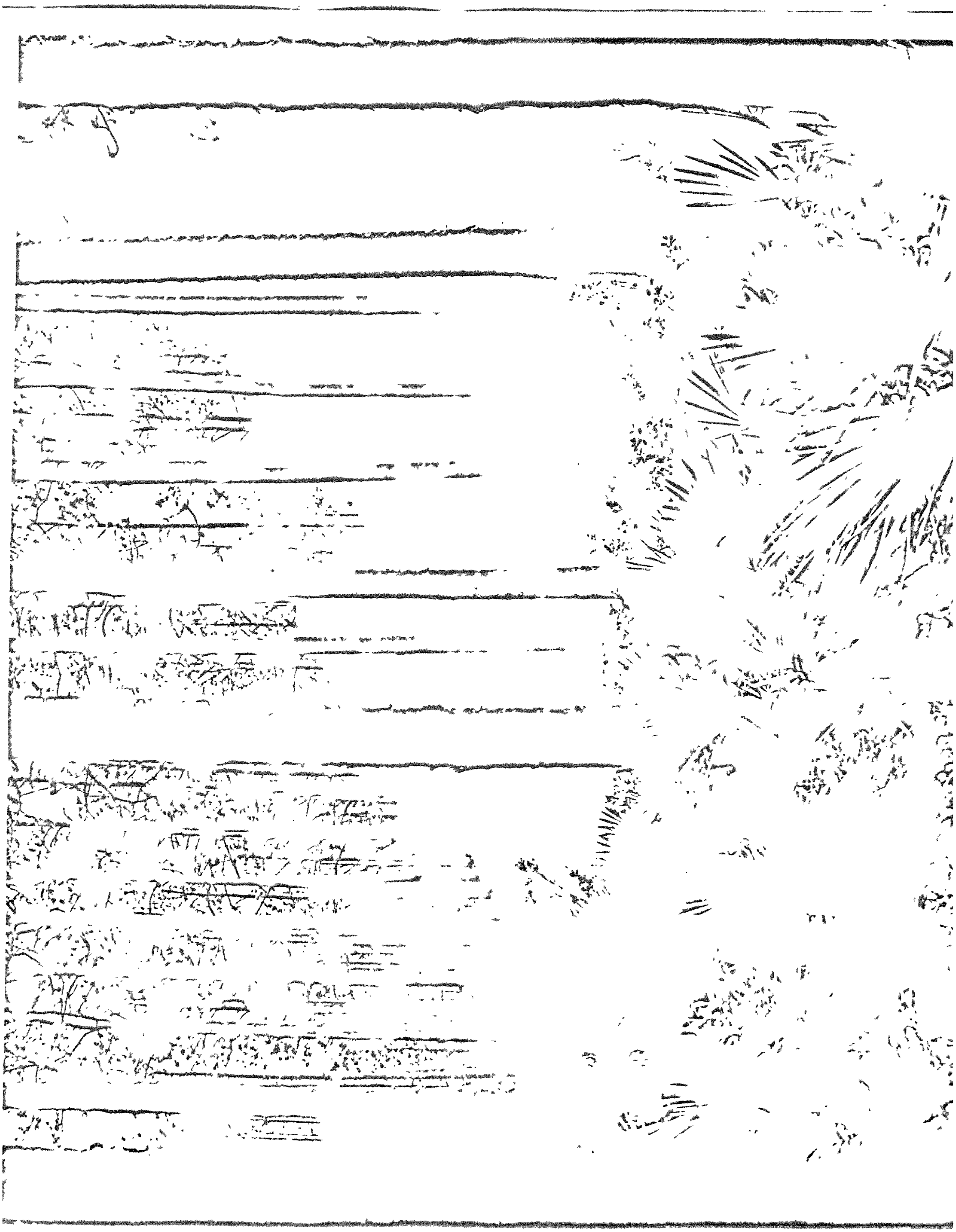
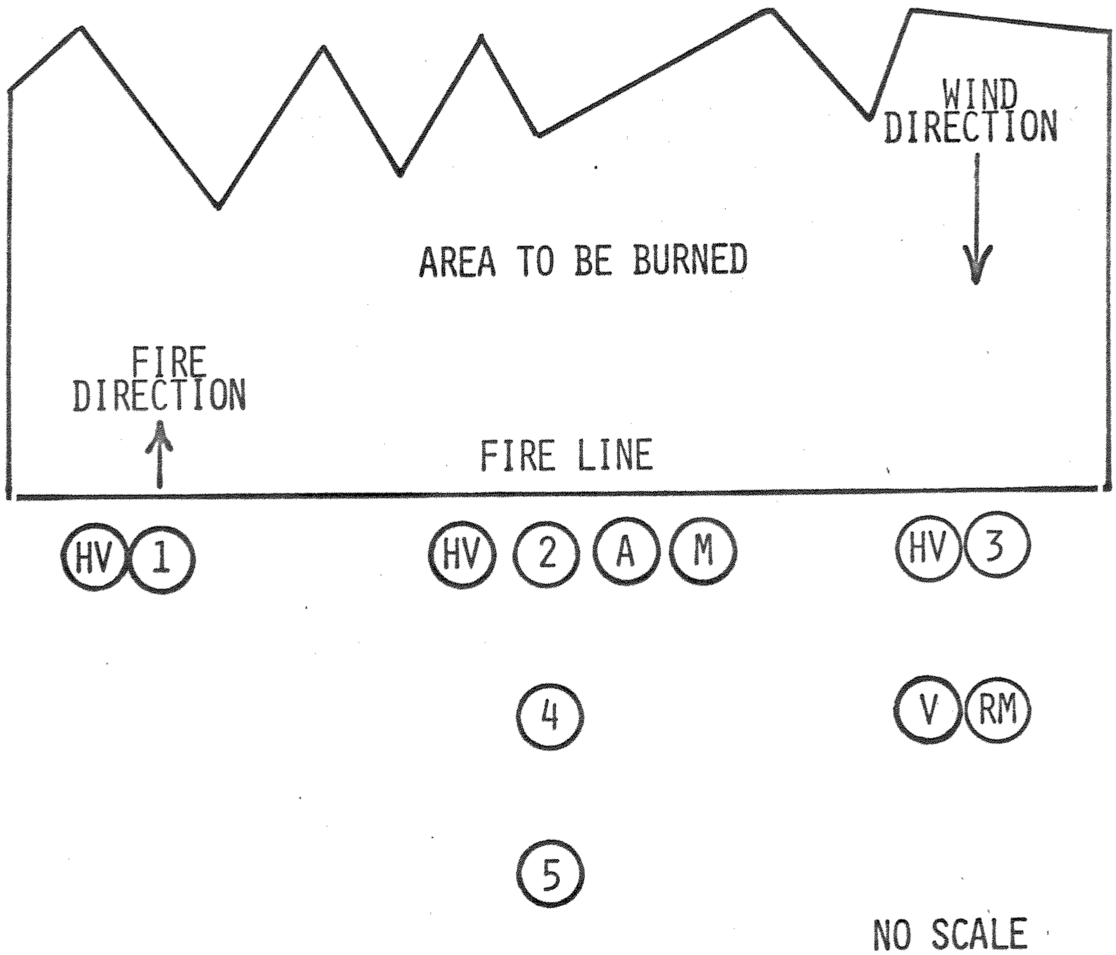


FIGURE 4 PLAN VIEW OF RELATIVE LOCATIONS OF THE EQUIPMENT USED FOR A TYPICAL TEST FIRE.



LEGEND

- MASTS (1 - 5)
- HV HIGH-VOLUME AIR SAMPLER
- A ANDERSEN PARTICLE SAMPLER
- M METEOROLOGICAL MAST WITH TOTALIZING ANEMOMETERS AT 6 AND 20 FT
- RM RECORDING WIND DIRECTION AND SPEED SENSORS AT 5 AND 20 FT
- V VACUUM SUPPLY PUMP

FIGURE 5 ISOPLETH LINES CONNECTING POINTS OF EQUAL CONCENTRATION (MG/M^3) FOR A PRESCRIBED BACKFIRE BURNING IN A PALMETTO-GALLBERRY FUEL TYPE.